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Is There a Relationship between Laser Therapy and Root Canal Cracks Formation? A Systematic Review

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Introduction: Crack formation has become an important issue for endodontists, as it can be decisive for the long-term prognosis of the endodontically treated tooth. Since the applicability of laser in endodontics has become frequent, this systematic review aimed to evaluate the association between laser therapy and the formation of cracks in the dentinal structure of the root canal. **Materials and Methods:** A search was performed in PubMed, Scopus, Web of Science, and Virtual Health Library, as well as in the gray literature, on September 24, 2021. Studies that evaluated the formation of cracks in human root dentin due to different types of lasers were included. The risk of bias was assessed following the modified version of the Consolidated Standards of Reporting Trials (CONSORT) checklist tool. A meta-analysis was performed to evaluate (*i*) the total number of crack incidences; (*ii*) complete crack formation; (*iii*) incomplete crack formation; (*iv*) intra-dentinal crack formation between ultrasonic tips and laser use. The mean difference was calculated with a 95% confidence interval in a fixed-effect model, the heterogeneity was tested using the I^2 index with level of significance of 5%. **Results:** Of the 22 studies included in this review, 15 have shown that lasers can form cracks in root dentin, including those that performed baseline assessment of samples. The meta-analysis confirmed no difference in crack formation between ultrasonic tips and laser devices. **Conclusions:** Laser therapy has been gaining prominence in endodontics and that irradiation can form and propagate cracks in the dentinal structure of the root canal assessed by *in vitro* studies. This is a critical concern for endodontists as it affects the strength and longevity of the tooth. Future research is encouraged to seek the standardization of good methodological practices and achieve establishing parameters to minimize harmful effects of laser on dentin.

Keywords: Crack; Dentin; Lasers; Root Canal Therapy; Systematic Review

Introduction

Laser (Light Amplification by Stimulated Emission of Radiation) is considered electromagnetic radiation, non-ionizing, having a single wavelength. There are a variety of laser devices developed and tested, such as Argon (Ar), Carbon Dioxide (CO_2), Neodymium YAG (Nd: YAG), Erbium YAG (Er: YAG) lasers, among others [1]. According to the type of laser, the contact with different tissues results in thermal, photochemical, and non-linear effects. It can be used for therapeutic, preventive, and aesthetic purposes, being well-tolerated by tissues [2].

Lasers can be classified into two main groups: (1) high power lasers or surgical lasers or HILT (high-intensity laser treatment), which promote thermal effect, with vaporization, cutting, and hemostasis of irradiated tissues, with surgical and ablative effects related to dental cavity preparations; and (2) low power lasers or therapeutic lasers or LILT (low-intensity laser therapy), widely used for therapeutic purposes and tissue biostimulation, providing more effective tissue repair, analgesia, anti-inflammatory and antisepsis action in the irradiated area, and acting mainly as accelerators in healing processes [2].

Several types of research have been developed to determine the best parameters and irradiation techniques to enable its use in different dental procedures [3]. The applicability of laser in Endodontics has become frequent, being a tool for conventional treatment, helping diagnose pulp vitality, capping, pulpotomy, analgesia, preparation, irrigation and antisepsis of root canals, and endodontic retreatment, periapical surgery, post-operative and endodontic failures [4]. While for para-endodontic surgery and cavity preparations, the high power laser is used, the use during conventional endodontic treatment and pulp diagnosis, low power laser is recommended [5].

Due to the increase in temperature generated by the laser both internally and on the external surface of the root canals, this method must be used judiciously with adequate cooling. Misuse can cause damage to the periodontal ligament and cracks in the dentinal structure [6].

Crack formation is a crucial issue for the endodontist as it determines the strength and longevity of the tooth after endodontic treatment. Much has been studied on the relationship between crack and mechanical chemical root canal preparation, mainly involving mechanized files [7, 8]. Nonetheless, studies have shown that the laser can initiate or propagate crack formation without consensus [9, 10]. It is believed that the dentin crack is responsible for the vertical fracture of the root and, consequently, tooth loss [3].

In this way, the study on the possibility of the laser causing cracks in the dentin structure becomes mandatory. There is a precise and safe definition of the parameters used in endodontic treatment. The present work aims to search the literature, through a systematic review, for studies that evaluated cracks in the root canal dentin structure caused by laser during endodontic procedures.

Materials and Methods

This systematic review was conducted following the PRISMA statement (Preferred Reporting Items for Systematic Analyzes and Meta-analyses) [11], and its protocol was registered in the Open Science Framework database (https://osf.io/2wmt5). The central question of this systematic review was to answer the following focused question: Is the use of laser in the root canal dentinal structure capable of generating cracks?

Eligibility criteria

The PIO strategy was used to select the studies, a variant of the PICOS structure (P: population, I: intervention, C: comparison, O: result, S: study design), which is used to investigate the effectiveness of interventions without a comparator. Whereas (P) = Root canal dentin structure; (I) = lasers; (O) formation of cracks. Two aspects were considered relevant for the inclusion of the studies: the use of laser for endodontic procedures and the use of human root dentin samples. Therefore, the included *in vitro* studies evaluated the formation of cracks in human root dentin due to different types of lasers.

As exclusion criteria, studies performed on non-human teeth or that did not assess the formation of cracks in root dentin were excluded, as were animal studies, case reports, book chapters, literature reviews, duplicate studies, conferences, editorials, theses and dissertations, panels, banners, and other non-experimental publications were excluded. In addition, studies that were not fully recovered were excluded.

Information sources

The broad search in the electronic databases was conducted on December 27, 2022, on PubMed, Scopus, Web of Science, and Virtual Health Library (VHL). Opensingle (http://www.opengrey.eu/, accessed on December 27, 2022) was consulted as gray literature, and a manual search in the references list of the included studies was also performed.

Search strategy

MeSh terms, entry terms, synonyms, related terms, and free terms referred to as "root canal dentin" and "lasers" were included in the search strategy. The terms were combined to refine the search results using the search strategy shown in Table 1.

Selection process

The identified documents were exported to the Mendeley Desktop software (Mendeley Ltd., London, UK), organized, and duplicates were automatically removed and manually checked. Two independent examiners (MRCC and SC) assessed the titles and abstracts of all studies, applied the eligibility criteria, and during the consensus meetings, discussed the doubts. If necessary, a complete reading of the article was performed to decide on the study's eligibility. Subsequently, all potentially selected works were read in full by two evaluators (MRCC and SC). Any disagreement between raters was arbitrated by a third author (BMP).

Data collection process and data items

Data extraction from the included articles was performed by three independent evaluators (MRCC, BMP, and SC). The main data collected were 1-Qualitative or Quantitative Work; 2-Author and year of publication; 3-Laser assessment goals; 4- Crack analysis of the sample before the experiment; 5-Experimental groups; 6-Experiment methodology; 7-Detailed results; 8-Main conclusions.

Table 1. Electronic database used and search strategy

Database	Search Strategy
PubMed	#1 (Lasers[MeSH Terms]) OR (Laser Therapy[MeSH Terms])) OR (Laser[Title/Abstract])) OR (Laser Therapies[Title/Abstract])) OR (Therapies, Laser[Title/Abstract])) OR (Therapy, Laser[Title/Abstract])) OR (Laser Vaporization[Title/Abstract])) OR (Laser Ablation[Title/Abstract])) OR (Laser Treatments, Nonablative[Title/Abstract])) OR (Scalpels, Laser[Title/Abstract])) OR (Knives, Laser[Title/Abstract])) OR (Laser Knife[Title/Abstract])) OR (Knife, Laser[Title/Abstract])) OR (Knifes, Laser[Title/Abstract])) OR (Laser Surgery[Title/Abstract])) OR (YSGG laser[Title/Abstract])) OR (YAG laser[Title/Abstract])) OR (laser tip*[Title/Abstract])) OR (laser beam*[Title/Abstract])) OR (Laser Treatment[Title/Abstract]) #2 (Dentin[MeSH Terms]) OR (Dental Pulp Cavity[MeSH Terms])) OR (Dentine[Title/Abstract])) OR (Cavities, Dental Pulp[Title/Abstract])) OR (Dental Pulp Cavities[Title/Abstract])) OR (Pulp Chamber[Title/Abstract])) OR (Pulp Chambers[Title/Abstract])) OR (Pulp Canal[Title/Abstract])) OR (Pulp Canals[Title/Abstract])) OR (Root Canal*[Title/Abstract])) OR (Canal, Root[Title/Abstract])) OR (Canals, Root[Title/Abstract])) OR (dentinal walls[Title/Abstract])) OR (root apices[Title/Abstract])) OR (root surface*[Title/Abstract])) OR (Dental Root Canal[Title/Abstract]) #3 (Crack[Title/Abstract]) OR (Cracking[Title/Abstract])) OR (Microcrack*[Title/Abstract])) OR (Micro-cracks[Title/Abstract])) OR (Endodontic microcracks[Title/Abstract])) OR (Dental cracks[Title/Abstract])) OR (apical cracks[Title/Abstract]))) OR (morphological characteristics[Title/Abstract])) OR (morphological change*[Title/Abstract])) OR (fissure*[Title/Abstract])) OR (fissuring[Title/Abstract])) OR (fracture*[Title/Abstract]) **#1 AND #2 AND #3**
Scopus	#1 (TITLE (lasers) OR TITLE (laser AND therapy) OR TITLE-ABS-KEY (laser) OR TITLE-ABS-KEY (laser AND therapies) OR TITLE-ABS-KEY (therapies, AND laser) OR TITLE-ABS-KEY (therapy, AND laser) OR TITLE-ABS-KEY (laser AND vaporization) OR TITLE-ABS-KEY (laser AND ablation) OR TITLE-ABS-KEY (laser AND treatments, AND nonablative) OR TITLE-ABS-KEY (scalpels, AND laser) OR TITLE-ABS-KEY (knife, AND laser) OR TITLE-ABS-KEY (laser AND knife) OR TITLE-ABS-KEY (knife, AND laser) OR TITLE-ABS-KEY (knifes, AND laser) OR TITLE-ABS-KEY (laser AND surgery) OR TITLE-ABS-KEY (laser AND beam*) OR TITLE-ABS-KEY (ysgg AND laser) OR TITLE-ABS-KEY (yag AND laser) OR TITLE-ABS-KEY (laser AND tip*) OR TITLE-ABS-KEY (laser AND treatment)) #2 (TITLE (dentin) OR TITLE (dental AND pulp AND cavity) OR TITLE-ABS-KEY (dentine) OR TITLE-ABS-KEY (cavities, AND dental AND pulp) OR TITLE-ABS-KEY (dental AND pulp AND cavities) OR TITLE-ABS-KEY (pulp AND chamber) OR TITLE-ABS-KEY (pulp AND chambers) OR TITLE-ABS-KEY (pulp AND canal) OR TITLE-ABS-KEY (pulp AND canals) OR TITLE-ABS-KEY (root AND canal*) OR TITLE-ABS-KEY (canal, AND root) OR TITLE-ABS-KEY (canals, AND root) OR TITLE-ABS-KEY (dentinal AND walls) OR TITLE-ABS-KEY (root AND apices) OR TITLE-ABS-KEY (root AND surface*) OR TITLE-ABS-KEY (dental AND root AND canal)) #3 (TITLE-ABS-KEY (crack) OR TITLE-ABS-KEY (cracking) OR TITLE-ABS-KEY (microcrack*) OR TITLE-ABS-KEY (micro-cracks) OR TITLE-ABS-KEY (dental AND cracks) OR TITLE-ABS-KEY (apical AND cracks) OR TITLE-ABS-KEY (morphological AND characteristics) OR TITLE-ABS-KEY (morphological AND change*) OR TITLE-ABS-KEY (fissure*) OR TITLE-ABS-KEY (fissuring) OR TITLE-ABS-KEY (fracture*)) **#1 AND #2 AND #3**
Web of Science	**#1** TITLE: (Lasers) OR TITLE: (Laser Therapy) OR TOPIC: (Laser) OR TOPIC: (Laser Therapies) OR TÓPICO: (Therapies, Laser) OR TOPIC: (Therapy, Laser) OR TOPIC: (Laser Vaporization) OR TOPIC: (Laser Ablation) OR TOPIC: (Laser Treatments, Nonablative) OR TOPIC: (Scalpels, Laser) OR TOPIC: (Knife, Laser) OR TOPIC: (Laser Knife) OR TOPIC: (Knife, Laser) OR TOPIC: (Knifes, Laser) OR TOPIC: (Laser Surgery) OR TOPIC: (Laser beam*) OR TOPIC: (YSGG laser) OR TOPIC: (YAG laser) OR TOPIC: (laser tip*) OR TOPIC: (laser treatment) **#2** TITLE: (Dentin) OR TITLE: (Dental Pulp Cavity) OR TOPIC: (Dentine) OR TOPIC: (Cavities, Dental Pulp) OR TOPIC: (Dental Pulp Cavities) OR TOPIC: (Pulp Chamber) OR TOPIC: (Pulp Chambers) OR TOPIC: (Pulp Canal) OR TOPIC: (Pulp Canals) OR TOPIC: (Root Canal*) OR TOPIC: (Canal, Root) OR TOPIC: (Canals, Root) OR TOPIC: (dentinal walls) OR TOPIC: (root apices) OR TOPIC: (root surface*) OR TOPIC: (dental root canal) **#3** TOPIC: (Crack) OR TOPIC: (Cracking) OR TOPIC: (Microcrack*) OR TOPIC: (Micro-cracks) OR TOPIC: (Endodontic microcracks) OR TOPIC: (Dental cracks) OR TOPIC: (apical cracks) OR TOPIC: (morphological characteristics) OR TOPIC: (morphological change*) OR TOPIC: (fissure*) OR TOPIC: (fissuring) OR TOPIC: (fracture*) **#1 AND #2 AND #3**
Virtual Health Library	((mh:(Dentin)) OR (mh:(Dental Pulp Cavity)) OR (dentinal walls) OR (Dentine) OR (Cavities, Dental Pulp) OR (Dental Pulp Cavities) OR (Pulp Chamber) OR (Pulp Chambers) OR (Pulp Canal) OR (Pulp Canals) OR (Root Canal*) OR (Canal, Root) OR (Canals, Root) OR (root apices) OR (root surface*) OR (dental root canal)) AND ((mh:(Lasers)) OR (mh:(Laser Therapy)) OR (Laser) OR (Laser Therapies) OR (Therapies, Laser) OR (Therapy, Laser) OR (Laser Vaporization) OR (Laser Ablation) OR (Laser Treatments, Nonablative) OR (Scalpels, Laser) OR (Knife, Laser) OR (Laser Knife) OR (Knifes, Laser) OR (Laser Surgery) OR (Laser beam*) OR (YSGG laser) OR (YAG laser) OR (laser tip*) OR (laser treatment)) AND ((Crack) OR (Cracking) OR (Microcrack*) OR (Micro-cracks) OR (Endodontic microcracks) OR (Dental cracks) OR (apical cracks) OR (morphological characteristics) OR (morphological change*) OR (fissure*) OR (fissuring) OR (fracture*))

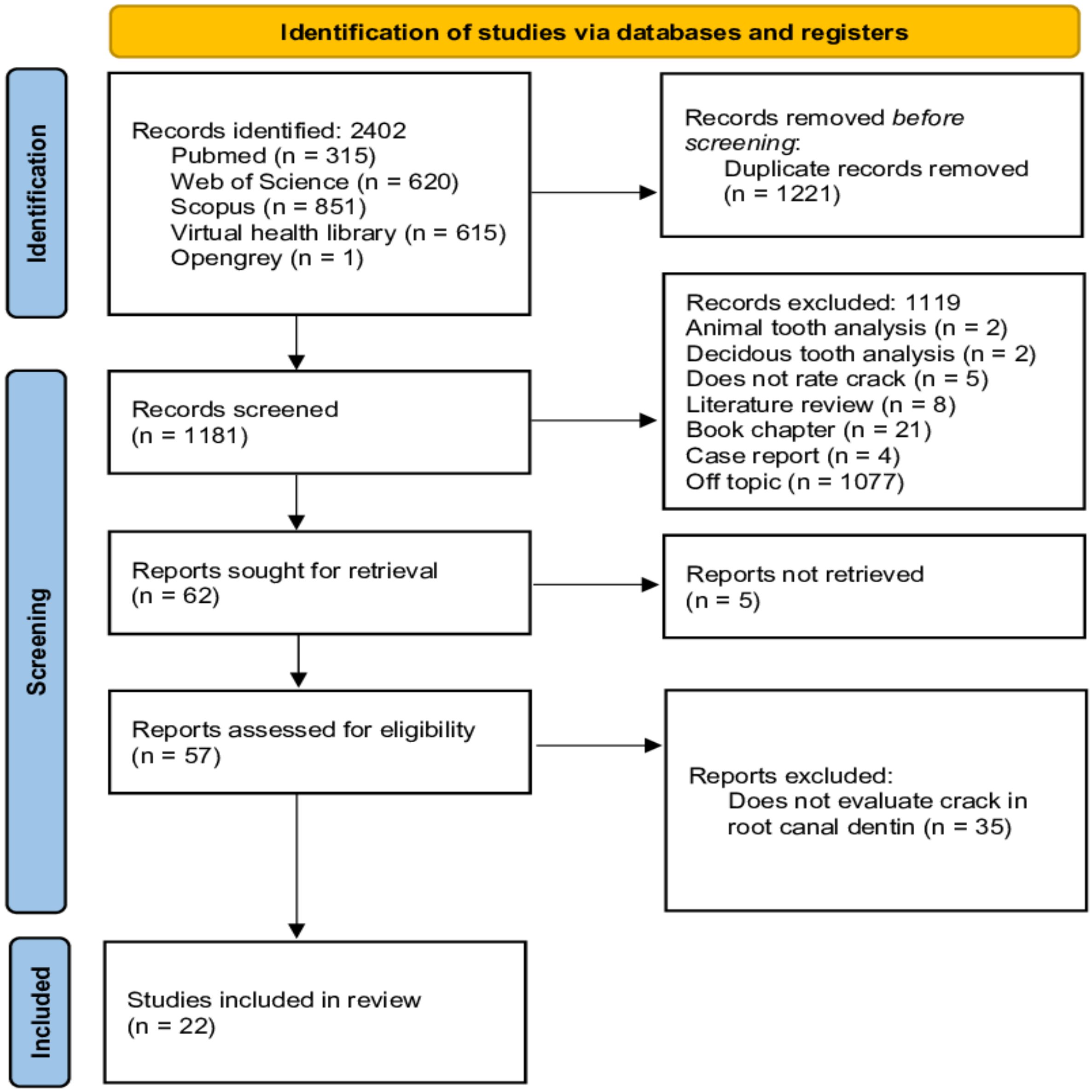

Figure 1. PRISMA flow diagram

Regarding the laser used in the studies, the following parameters were retrieved: 1-Author and year; 3-Type of radiant; 4-Wavelength; 5-Power; 6-Energy and Frequency; 7-Pulse duration; 8-Exposure time; 9-Optical fiber size.

Studies risk of bias assessment

The risk of bias in the methodologies and reported data of the included studies were analyzed by three independent evaluators (MRCC, BMP, and SC). Since there are currently no established guidelines for assessing the quality of *in vitro* design studies, this review employed a modified version of the Consolidated Standards of Reporting Trials (CONSORT) tool, which was developed to assess the quality of studies in dentistry [12]. The tool is comprised in the evaluation of the following 14 criteria: 1-related to the presence of aim and/or defined hypothesis; 3-bout sample size calculation report; 6, 7 and 8-regarding the occurrence of random allocation, the method used and the report on who carried out this step; 9-whether there was a blinding process; 10-about statistical methods used; 11-regarding the detailed report of results; 12-regarding the detailed report of discussion, including a limitation statement; 13-sources of funding; 14-whether there was a full trial protocol available or this is explained in detail in the manuscript. The studies were evaluated and received a "Yes" if they satisfactorily addressed the domain, "No" if they did not report the specific criterion [12].

Synthesis methods and effect measures

A meta-analysis was performed with the studies that compared the incidence of crack formation with ultrasonic tips and laser devices. RevMan software (Review Manager version 5.3.; the Cochrane Collaboration; Copenhagen, Denmark) was used for quantitative analysis. Since the studies classified the types of cracks as complete, incomplete, and intra-dentinal, four analyzes were performed to assess comparisons between two studies, regarding i) the total number of crack incidences; ii) complete crack formation; iii) incomplete crack formation; iv) intra-dentinal crack formation.

Mean, standard deviation (SD), and the total number of samples from each group (ultrasonic tips and laser) were included. Thus, the mean difference (MD) was calculated with a 95% confidence interval (CI). A fixed-effect model was employed [13], and heterogeneity was tested using the I^2 index with level of significance of 5%.

Results

Study selection

The search in the electronic databases retrieved 2514 articles, of which 1264 were duplicates. When applying the eligibility criteria in titles and abstracts, 1142 articles were excluded since they were out of the topic of interest, eight literature reviews, four case reports, two papers were excluded because they analysed deciduous teeth and two in animal teeth, five for not evaluating cracks. Five studies were not retrieved in full. There remained 61 studies that were read in total, and during the screening process, 39 were excluded for not analysing the incidence of cracks in root canal dentin. Thus 22 articles met the eligibility criteria and were included in this systematic review [3, 6, 9, 10, 14-31] (Figure 1).

Study characteristic

The main characteristics of the included studies are reported in Table 2. The main objective of ten articles was to generally evaluate the effects of laser on root canal walls [6, 9, 22, 24, 25, 27-31], while other studies sought to evaluate dentin ablation or root resection and root-end cavity preparation [10, 15-19, 26]. Four studies have specified that analyses aimed at adjuvant procedures during root canal treatment referred to cleaning and shaping the root canal and smear layer removal [3, 9, 14, 21].

Regarding the number of samples used in the analysis, it ranged from 5 [28] to 140 [29], while only two studies did not report the number of specimens [23, 30]. It is important to emphasize that most of the articles did not perform any crack analysis procedure before the execution of the experiments proposed in the methodology of each report [6, 16, 18, 21-26, 28-31]. At the same time, one study claimed to perform such a preliminary analysis without outlining how assessment tool [15], others specified the use of preliminary analysis by stereomicroscope [9, 14, 19], microscope [3, 10] and light microscopy [27]. Regarding the methodology for evaluating crack formation after laser exposure, most of the studies used SEM [6, 9, 10, 14-16, 18, 21-31]. However, Kimura *et al*. [26] also employed analysis in confocal laser scanning microscopy, and other studies used stereomicroscope [14, 17, 19, 30] or light microscopy [3, 28].

The Nd: YAG laser was the most used type among the articles [21, 23, 25, 27-29], followed by the CO_2 laser [22, 26, 28-30], Er,Cr: YSGG laser [10, 15, 19, 24] and Er: YAG laser [16-18]. As a comparator group, ultrasonic tips [10, 16-19] and burs [10, 16, 17] were used. The parameters of the lasers used in each study are described in Supplementary Materials Table 1 available at Mendeley Data (https://data.mendeley. com/datasets/ sjgg4xbbt2/1).

Risk of bias in studies

Only one study received a "No" response in the abstract domain, for not presenting a rationally structured abstract on the key theme [20]. As well as only one included study [15] did not provide an introduction that required by the modified CONSORT tool. All included studies postulated their aims and/or hypotheses at the end of the introduction, as well as adequately presented their interventions, measurement methods and outcomes found. Ten studies reported the random allocation of samples among the included groups [3, 14, 16, 19, 20, 22-24, 29, 31]. In contrast, no included study reported performing a sample size calculation and whether an author other than the experiment's executor performed the randomization process. Only eight included studies assumed the limitations faced during the execution of the studies [3, 6, 14, 17, 18, 21, 25, 26].

The risk of bias assessment of the included studies is summarized in Table 3.

Results of qualitative synthesis and meta-analyses

The synthesis of the results of the included studies was reported in Table 4. Of the 22 studies included in this review, 15 studies showed that the laser could form cracks in the root canal walls [3, 6, 9, 14, 18, 21-25, 27-31]. It has been shown that the parameters used during laser application affect the incidence of cracks, which increase in intensity with increasing power, and pulse duration increases crack formation [3, 21, 23, 30, 31]. There is even an increase in the formation of cracks about the lack of moisture in the root canal during irradiation [14, 24].

Table 2. Main characteristics of the included studies

Author/Year	Sample Size	Laser assessment goals	Previously rated crack/ methods	Interventions groups	Assessment methodology
Godiny *et al.* [14]	100	Cleaning and shaping of root canal	Yes; Stereomicroscope	Diode laser irradiated groups varying the power of 1.5, 2, 3 and 4 W in humid root canals and in dry canals. The control was humid and dry non-irradiated teeth.	Stereomicroscope
Alhadi *et al.* [9]	18	Smear layer removal and Effects of laser in root canal walls	Yes; Radiographically and stereomicroscope	Group A: 5 ml of 17% EDTA for 1min Group B: 5 ml of 17% EDTA for 1 min + Laser Diode	SEM
Almiran *et al.* [15]	10	Root resection and root-end cavity preparation	Yes; Does not mention how	Only one group: Er, Cr: YSGG laser.	SEM
Braun *et al.* [3]	40	Additional disinfection protocol	Yes; Microscope	Group A: Constant laser Group B: Interval Diode laser Group C: Calcium hydroxide Group D: Untreated (control)	Transmitted-light microscopy
Ayranci *et al.* [16]	30	Root resection	No	Group A: Er:YAG laser Group B: Tungsten carbide burs Group C: US retrotip	SEM
Aydemir *et al.* [17]	60	Root resection and root-end cavity preparation	Yes; Stereomicroscope	Group A: Tungsten carbide burs Group B: Er:YAG laser Group C: Teeth were resected with an Er:YAG laser, and root end-cavities were made with an US retrotip	Stereomicroscope
Aydemir *et al.* [18]	50	Root-end cavity preparation	No	Group A: Ultrasonic (US) retrotips Group B: Er: YAG laser Group C: Untreated (control)	SEM
Camargo Villela Berbert *et al.* [10]	60	Root resection and root-end cavity preparation	Yes; Operate microscope.	Root resection: Group A: Zekrya bur Group B: US tip Group C: ErCr:YSGG laser End cavities: Group A: US tip 1 Group B: US tip 2 Group C: ErCr:YSGG laser	SEM
Rahimi *et al.* [19]	60	Root-end cavity preparation	Yes; Stereomicroscope	Group A: US retrotip Group B: ErCr:YSGG laser	Stereomicroscope
Wallace [20]	36	Root-end cavity preparation	Yes; Stereomicroscope	Only Waterlase laser	Stereomicroscope
Niccoli Filho [6]	10	Effects of laser in root canal walls	No	Group A: Copper Vapor Laser Group B: Untreated (control)	SEM
Khabbaz *et al.* [21]	21	Cleaning and shaping of root canal	No	Group A: Free-running Er:YAG laser varying the pulse energy 30 to 70 mJ, pulse frequency 1 and 4 Hz, 20 to 150 pulses with 100 µs. Group B: Q-switched Er:YAG laser in the same parameters Group C: Untreated (control)	SEM
Anić *et al.* [29]	140	Effects of laser in root canal walls	No	Group A: Nd:YAG laser Group B: CO2 laser Group C: Argon laser Group D: Untreated (control)	SEM
Barone *et al.* [22]	30	Effects of laser in root canal walls	No	Group A: Focused CO2 Laser Group B: Non-Focused CO2 Laser	SEM

Author/Year	Sample Size	Laser assessment goals	Previously rated crack/ methods	Interventions groups	Assessment methodology
				Group C: Untreated (control)	
Kaitsas *et al.* [25]	20	Effects of laser in root canal walls	No	Group A: Nd:YAG laser Group B: Untreated (control)	SEM
Lin *et al.* [23]	NM	Repair root fracture	No	Nd:YAG laser in a pulse frequency of: Group A: 30 pulses per sec (pps) Group B: 20 pps Group C: 10 pps Group D: Untreated (control)	SEM
Yamazaki [24]	60	Effects of laser in root canal walls	No	Two groups used the Er,Cr:YSGG laser, with and without cooling. Subdivided into 6 subgroups employing powers ranging from 1 to 6 W	SEM
Kimura *et al.* [26]	30	Dentin ablation	No	CO2 laser with: Group A: 26 mJ/pulse Group B: 30 mJ/pulse	Confocal laser scanning microscopy (CLSM) and SEM
Serafetinides [27]	30	Effects of laser in root canal walls	Yes; Light microscopy	Nd:YAG laser in a wavelength at: GroupA: 1064 nm Group B: 532nm	SEM
Brugnera *et al.* [28]	5	Effects of laser in root canal walls	No	Group A: CO2 laser Group B: Nd:YAG laser	Light microscopy and SEM
Read *et al.* [30]	NM	Effects of laser in root canal walls	No	CO2 laser with 15 W, 11 W, 8 W, 6W, 4 W and 2 W. Fluences used ranged from 2.1 to 625.0 J/cm	Stereomicroscope and SEM
Stabholz *et al.* [31]	15	Effects of laser in root canal walls	No	ArF-193 nm excimer laser in different fluences: 0.2 J/cm^2, 0.5 J/cm^2, 1 J/cm^2, 5 J/cm^2, 15 J/cm^2 Control: Untreated	SEM

SEM: Scanning Electron Microscope; US: Ultrasonic, NM: Not mentioned, W: Watt

Table 3. Quality assessment of the *in vitro* studies according to modified version of the CONSORT checklist tool

Studies	Item														
	1	**2a**	**2b**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Godiny *et al.* [14]	Yes	Yes	Yes	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes
Alhadi *et al.* [9]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	No	No	Yes
Almiran *et al.* [15]	Yes	No	Yes	Yes	Yes	No	No	No	No	No	No	Yes	No	No	Yes
Braun *et al.* [3]	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes
Ayranci *et al.* [16]	Yes	Yes	Yes	Yes	Yes	No	Yes	No	No	Yes	Yes	Yes	No	No	Yes
Aydemir *et al.* [17]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	No	Yes
Aydemir *et al.* [18]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	No	Yes
Camargo Villela Berbert *et al.* [10]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	No	Yes	Yes
Rahimi *et al.* [19]	Yes	Yes	Yes	Yes	Yes	No	Yes	No	No	Yes	Yes	Yes	No	No	Yes
Wallace [20]	No	Yes	Yes	Yes	Yes	No	Yes	No	No	No	No	Yes	No	No	Yes
Niccoli Filho [6]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No	Yes	Yes	No	Yes
Khabbaz *et al.* [21]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No	Yes	Yes	Yes	Yes
Anić *et al.* [29]	Yes	Yes	Yes	Yes	Yes	No	Yes	No	No	No	Yes	Yes	No	No	Yes
Barone *et al.* [22]	Yes	Yes	Yes	Yes	Yes	No	Yes	No	No	Yes	No	Yes	No	No	Yes
Kaitsas *et al.* [25]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No	Yes	Yes	No	Yes
Lin *et al.* [23]	Yes	Yes	Yes	Yes	Yes	No	Yes	No	No	No	No	Yes	No	Yes	No
Yamazaki [24]	Yes	Yes	Yes	Yes	Yes	No	Yes	No	No	No	No	Yes	No	Yes	No
Kimura *et al.* [26]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No	Yes	Yes	Yes	Yes
Serafetinides [27]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No	Yes	No	No	Yes
Brugnera *et al.* [28]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No	Yes	No	No	Yes
Read *et al.* [30]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No	Yes	No	Yes	Yes
Stabholz *et al.* [31]	Yes	Yes	Yes	Yes	Yes	No	Yes	No	No	No	No	Yes	No	No	Yes

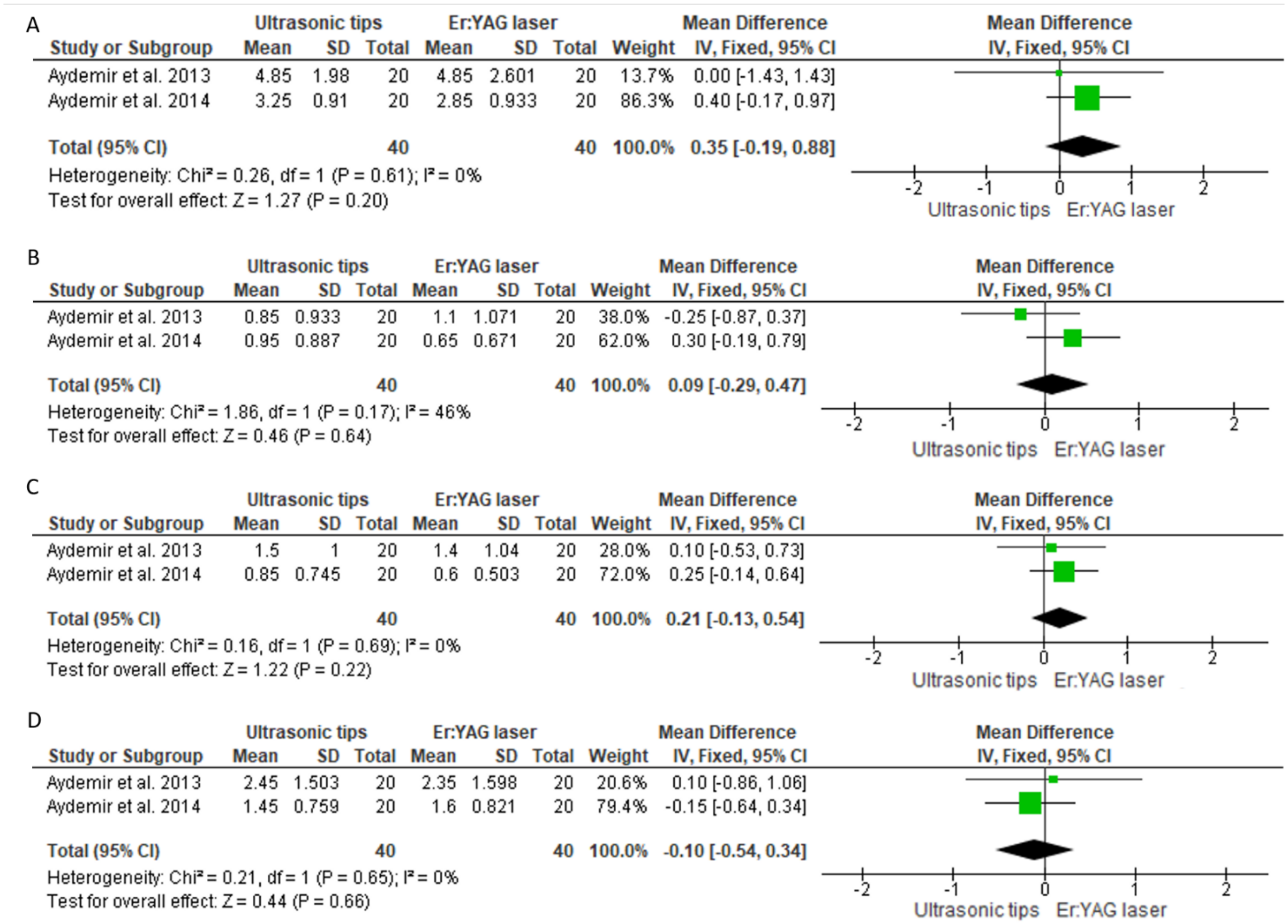

Figure 2. Mean, standard deviation (SD), and the total number of samples from each group (ultrasonic tips and laser) were included. A – Evaluation of the formation of the number of total cracks using 40 samples per group; B - Evaluation of complete crack formation using 40 samples per group; C -Evaluation of incomplete crack formation using 40 samples per group; D - Evaluation of intra-dentinal crack formation using 40 samples per group

When the use of laser was compared to the use of ultrasonic tips for apicectomy procedures, while one study showed significantly greater crack formation with the use of ultrasonic tips [16], four studies did not find a significant difference between laser and ultrasound [10, 17-19], being that two of them still point out that the laser does not influence the significant formation of cracks in the root canal wall [10, 17].

The meta-analysis confirmed these findings, which included two studies [17, 18] and four comparisons, including 40 samples in total for each comparison, of the mean and standard deviation of cracks formed after the use of ultrasonic tips *vs* Er: YAG laser in root-end cavity preparation.

No statistical differences were observed considering the total number of crack incidences (MD 0.35 [95% CI, −0.19, 0.88] *P*=0.20) without heterogeneity for this analysis (i^2=0%) as shown in Figure 2A; the complete crack formation (MD 0.09 [95% CI, −0.29, 0.47] *P*=0.64) with moderate heterogeneity for this analysis (i^2=46%) as shown in Figure 2B; for the incomplete crack formation (MD 0.21 [95% CI, −0.13, 0.54] *P*=0.22) without heterogeneity (i^2=0%) as shown in Figure 2C; and finally to intra-dentinal crack formation analyses (MD -0.10 [95% CI, −0.54, 0.34] *P*=0.66) without heterogeneity (i^2=0%) as shown in Figure 2D.

Discussion

The endodontic treatment aims for the decontamination of the root canal with the greatest possible preservation of dental tissue [3]. Even though conventional endodontics already has a high success rate (85%-95%), there are still cases where it is insufficient [18]. Increase the success rate, the laser has become an attraction for endodontic researchers who seek to improve the performance of endodontic procedures by associating the properties of laser therapy.

Table 4. Main conclusions of the included studies

Author/Year	Detailed result	Main conclusions
Godiny *et al.* [14]	The frequency of microcrack is increased by rising laser power and under dry root canal condition.	The laser produced cracks in the dentin, but the optimal power of a 1.5W diode laser at the wavelength (980nm) for root cleaning and disinfection, as well as canal moisture, can generate minimal damage to the hard tissue.
Alhadi *et al.* [9]	Laser Diode+EDTA showed more cracks than EDTA alone.	The 810 nm diode laser can cause more dentin erosion and greater mineral loss when combined with EDTA.
Almiran *et al.* [15]	There was fluctuation in the results, ranging from the absence of cracks to the formation of 7 cracks per sample.	No cracking pattern was observed in the root irradiated with Er,Cr:YSGG laser.
Braun *et al.* [3]	The middle and apical root sections in the constant laser group showed the significantly largest amount of crack formation in comparison with the other groups. No statistically significant differences between the interval laser group, the calcium hydroxide group, and the control group.	The continuous laser produced microcracks in the dentin of the canal, while the interval laser protocol seems to be able to prevent such cracks.
Ayranci *et al.* [16]	US showed higher cracks compared to the other groups.	US tips provokes a larger number of cracks when compared to the Er: YAG laser and tungsten carbide bur.
Aydemir *et al.* [17]	Cracking was not significantly different between the groups.	The laser resection and root-end preparation technique did not influence the number or type of cracks formed on the root surfaces.
Aydemir *et al.* [18]	Both produced cracks, however no statistically significant difference was detected between the US and laser groups.	The Er: YAG laser irradiation produces cracks when used for the root-end resection.
Camargo Villela Berbert [10]	There were no cracks or fractures on root-end surfaces or resected root-ends after preparation.	The 3 methods evaluated did not cause any injury to the root-end surface, but the laser removed more dentin than US retrotips and should be used with care to avoid overpreparation.
Rahimi *et al.* [19]	Cracking was not significantly different between the groups.	Only one crack was found in US retrotip group while no cracks were found in laser groups.
Wallace [20]	No cracks were evident using the GSM at 12× magnification. Forty-eight h following immersion in 0.004% methylene blue dye, two investigators independently examined the resected root ends with the GSM 12× magnification and the FSM at 40× magnifications with transillumination, and once again no cracks were found.	The Waterlase laser does not produce a clinically relevant rate of cracking when used to make endodontic root-end preparations.
Niccoli Filho [6]	Irradiation with the Copper Vapor Laser produced the formation of cracks.	Copper Vapor Laser can change dentin morphology, with the formation of cracks, melting and craters in the dentin wall.
Khabbaz *et al.* [21]	Free-running Er:YAG laser at the frequency of 1Hz did not produce cracks, except for a single sample irradiated with 70mJ and 40 . Above 50 pulses at the frequency of 4Hz produced a crack in all samples. While Q-switched laser produced cracks in all parameters except 1 Hz, 30 mJ, and 20 to 40 pulses.	Both lasers used produced cracks, more frequently for the Q-switched Er:YAG laser group.
Anić *et al.* [29]	The dentin irradiated with CO2 laser showed cracks in the middle and apical thirds, this one with more severity.	The dentin irradiated with CO2 laser showed more cracks.
Barone *et al.* [22]	Focused CO2 Laser exhibited more zones of heat cracking than Non-focused CO2 Laser.	Although both laser modes resulted in changes to the treated root surface specimens, Focused CO2 Laser showed severe damages to dentin surfaces such as craters and fissures.

Kaitsas *et al.* [25]	Cracks were visible in the laser treated areas.	Morphological damage to dentin can be caused by laser applicability.
Lin *et al.* [23]	The Nd-YAG laser at pulse frequencies of 10 pps showed no cracking, while 20 and 30 pps exhibited crack formation.	The Nd-YAG laser with an energy of 150 mJ / 10 pps was not sufficient to cause cracks, while the increase in pulse frequency is related to the appearance of cracks.
Yamazaki [24]	The group without cooling showed cracks starting at 2 W, which increased in intensity with increasing power. The cooled group showed no significant cracks.	The group irradiated without cooling showed areas of carbonization and crack formation while little or no change was observed in the group irradiated with cooling.
Kimura *et al.* [26]	The SEM did not identify crack formation in the dentin, while the CLSM detected small cracks in the subsurface layer.	The irradiation pattern used affected only the superficial layer of the dentin, being less harmful during dentinal ablation.
Serafetinides [27]	The Nd:YAG laser at a wavelength of 532 nm was associated with intense crack formation, while at a wavelength of 1064 nm no crack was detected.	The Nd:YAG laser in a wavelength at 532nm was associated with intense crack formation and dentin melting, presenting closed dentin.
Brugnera *et al.* [28]	Both lasers produced some cracks of varied depths in all samples.	The light microscopy revealed some circumscribed carbonized areas with some cracks of varied depths in all samples.
Read *et al.* [30]	All samples showed visible cracks reaching up to 15mm in width. The incidence of cracks was directly proportional to the increase in energy.	The effects of CO2 laser on irradiated dentin ranged from minimum effect at low energy to charring, "vitrification" of dentin, cratering and cracking formation at higher energy.
Stabholz *et al.* [31]	The ArF-193 nm excimer laser on the fluence units of 0.2, 0.5 and 1 J/cm2 did not have deleterious effects on the irradiated dentin, but at the fluence of 5 and 15 J/cm2 there was cracks formation.	The area irradiated with laser at fluence 5 J/cm² and 15 J/cm² showed a significant dentin removal resulting in the formation of cracks, with an increase in depth in relation to the increase in fluence.

SEM: Scanning Electron Microscope; *US: Ultrasonic, NM: Not mentioned, W: Watts*

Endodontic treatment failures occur mainly due to the permanence of microorganisms in the root canal system [32]. However, endodontists have used low-level lasers as an adjuvant tool in decontamination. Previous studies have shown that the use of laser in the reduction of microbial inside the root canal is significant as a supplementary disinfectant strategy, whether used alone [33] or accompanied by disinfectant or photosensitizer solutions in photodynamic therapy approach [34-36]. On the other hand, a high-power laser has been frequently used in apical surgery and obliteration of dentinal tubules through dentin marbling [5].

It is worth mentioning that cracks and microcracks remain a concern in endodontics as this crack line can propagate due to occlusal forces and could result in tooth fracture [37]. Hence, the presence of cracks is considered a frustration for clinicians and patients due to its subjective and vague symptoms, an unpredictable prognosis becoming a restorative challenge [38]. Thus, this systematic review of the literature sought to analyze the incidence of cracks caused by laser therapy in the dentin root structure.

Regarding the assessment of the risk of bias and methodological quality assessment of the included studies, in the methods part, studies that did not report the randomization process had their scores lowered [6, 9, 10, 15, 17, 18, 21, 25-28, 30]. The use of random allocation, even *in vitro* designed studies, is considered essential so that the distribution of samples does not interfere with the results [39, 40]. It is also worth mentioning that the blinding of operators of *in vitro* studies may be limited due to the application of the intervention. However, it is indicated that the outcome examiners are blinded to reduce methodological bias in the intention of the researchers [40]. In this domain, only five studies reported blinding of examiners [3, 9, 16, 19, 22].

Only nine studies in this review reported the prior assessment of the presence of cracks and microcracks in the samples before undergoing the intervention, most using microscopic techniques [3, 9, 10, 14, 17, 27], two by stereomicroscope [19, 20] and only Almiran *et al.* [15] did not mention how this evaluation was carried out since there is a possibility that the cracks observed after the intervention was already there in the baseline of the samples resulting from the extraction process or from the storage conditions where the dehydration of the tooth is sufficient to cause dentinal defects [41], the preliminary analysis of this phenomenon is essential to outcomes validation of *in vitro* studies that evaluate cracks in extracted human teeth.

Therefore, considering only the studies that evaluated the presence of cracks in the samples during the baseline, most pointed to the ability of laser irradiation to cause cracks in dentin. This trend based on these studies suggested an association between the use of laser and cracks formation in human root dentin, assessed by in vitro studies since it was related that all procedures prior to irradiation did not cause the formation of cracks in the samples and those where cracks were identified were replaced [3, 9, 14, 15, 17, 27].

Similarly, when considering all included studies, the results have shown that laser irradiation on the dentinal structure of the root canal can form cracks [3, 6, 9, 14, 15, 18, 21-25, 27-31]. The harmful effect on dentin structure from lasers is mainly caused by the absorption of the beam by the dentin water and consequent considerable increase in temperature in the irradiated area, even for a short period, leading to vaporization and melting of the dentin forming the cracks [6, 24, 27, 31]. Furthermore, Kaitsas *et al.* [25] adds that at the point of laser application, there is an even more significant increase in temperature and corroborates with Braun *et al.* [3], who reported results showing greater cracks near the coronal third where the application was performed and less in the apical third.

Concerns that could be solved by using proper dentin cooling and correct parameters of laser use [21] since tissue responses to lasers are influenced by irradiation parameters (i.e., repetition rate, pulse energy, the wavelength, and optical properties of the tissue) [3, 21-23]. Barone *et al.* [22] showed that the use of focused CO2 laser in continuous mode caused a significantly higher incidence of cracks and microcracks when compared to non-focused CO2 laser in pulsed mode, which showed a homogeneous layer of dentin without deep cracks. Similarly, Braun *et al.* [3] reported higher incidences of the crack in the use of continuous diode laser, while the pulse interval protocol did not produce such cracks. Some studies [14, 21, 23, 30, 31] corroborate these findings by showing that increasing power and pulse frequency significantly increase crack formation.

Another device widely used in endodontics is the ultrasonic tips, which have become an important adjunct to endodontic therapies, improving the quality of procedures. Its applicability ranges from cleaning and shaping to endodontic surgical approaches [42]. In this systematic review, five studies compared crack formation between the application of lasers and ultrasonic tips without consensus [10, 16-19]. The meta-analysis performed in this review confirmed the hypothesis that there is no statistically significant difference in comparing crack formation between ultrasonic tips and laser devices on root-end cavity preparation. However, it is essential to mention that this analysis was limited to a comparison between only two studies.

In qualitative analysis, although Camargo Villela Berbert *et al.* [10] found greater dentin removal with the laser, there was no formation of cracks for both the ultrasonic tips and the laser. Rahimi *et al.* [19], Aydemir *et al.* [18] and Aydemir *et al.* [17] found no significant difference between both devices. On the other hand, Ayranci *et al.* [16] reported a significant increase in cracks after using ultrasound in apical surgery, encouraging the use of laser. Besides, it is worth mentioning that the laser, compared to ultrasound, mainly decreases the chance of contamination of adjacent tissues and presents advantages such as the absence of pain and vibration [43]. In addition, the vibration is the probable cause of the formation and propagation of cracks by the ultrasound, increasing the incidence of cracks when using the ultrasonic tips at high frequencies [44].

In addition, it is worth mentioning that the studies that compared the formation of cracks comparing laser devices with burs did not show significant differences [10, 16, 17]. Therefore, it is worth reflecting on whether the use of conventional [17], such as burs, would still be more applicable since the use of lasers in endodontics is still expensive and, consequently, limited.

There are limitations inherent to the study design and the heterogeneity of methodological resources used. First, the lack of reporting the age of the donor patients of the teeth used in the samples would undoubtedly imply the compositional structure of dentin and its crack pattern. In addition, the fact that the time and mode of storage of the tooth before exposure is unknown among the included studies becomes a limitation since the dehydration process or prolonged hydration could certainly infer mineral changes in root dentin. The diversity of lasers used in the studies with different parameters makes it difficult to determine which type of laser and parameters would be the least harmful concerning crack formation.

In addition, as the scanning electron microscope was the methodology most used to analyze the samples involved in the included studies, there is a relationship between the formation of cracks and artifacts produced during the preparation of the samples to be taken to SEM, mainly for the vacuum sputter-coating [30]. This fact was also pointed out by Aydemir *et al.* [18], who attributed the similarity of intra-dentinal specific crack type in the control group without intervention and the resulting experimental gives analysis by SEM. However, Read *et al.* [30] showed that an anterior stereomicroscopic analysis of samples taken to SEM could work to find posterior cracks formed during samples' processing.

Although the techniques used to assess cracks on dentin are valid, microcomputed tomography (micro-CT) was not reported by any of the included studies. The Micro-CT was introduced to analyze cross-sectioned root canals and the role of the three-dimensional root structure. This innovation could be achieved by the new kinds of software and hardware to evaluate the measured data created by micro-CT. Currently, this technology is used in endodontics to analyze the effects of instrumentation by different rotary instruments, including to assess dentin cracks [45, 46]. It could be perfectly applied to search for cracks caused by the laser, including identifying the formation or propagation of cracks beyond the visible surface observed by the microscopic tools used in the included studies.

Another possible limitation regarding this systematic review was that five studies were not retrieved as full text. Nonetheless, the authors attempted to retrieve by emailing the authors of the primary studies, up to five times, without success as there was no response. Therefore, five studies were excluded from the synthesis of results [47-51].

Despite the evidence pointing to a tendency for crack formation during different laser devices in endodontics, several variables infer caution in extrapolating this result. As lasers are becoming popular in the field of endodontics, transposing the results of this systematic review to a clinical situation requires prudence, even though because the *in vitro* sets prevent the periodontal ligament from exerting its absorptive function in the use of instruments inside the root canal [52]. Therefore, future research should be directed towards standardization of good methodological practices and establishing standardized parameters that minimize such harmful effects of laser on dentin [21] and thus further encourage the use of this device to improve endodontic procedures.

Conclusion

According to the results, this systematic review pointed out that laser irradiation of root canal dentin can form and propagate cracks in the dentinal structure of the root canal assessed by *in vitro* studies.

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